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A unified hybrid compact model of β-Ga_2O_3 Schottky barrier diodes for mixer and rectifier applications

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Dear editor,

β-gallium oxide (β-Ga_2O_3) was proposed as a new candidate for next-generation power devices in 2010 [1]. When applied in unipolar power devices, it is superior to SiC and GaN because of preferable material properties [2]. Power devices are essential components in modern energy systems. In the past few years, β-Ga_2O_3 power devices have achieved substantive progress. The achievements include a β-Ga_2O_3 Schottky barrier diode (SBD) with a record high power figure of merit of 0.95 GW/cm^2 [3]. Among the various β-Ga_2O_3 power devices, the fabrication technology of SBD is the simplest and the most mature. Thus, researchers have paid the most significant attention to β-Ga_2O_3 SBDs, and their application in AC/DC [4].

The applications of power devices are inseparable from power electronic circuit design. A compact model is the bridge of device and circuit design. Currently, a variety of physical models of β-Ga_2O_3 SBDs have been reported [5,6], but such models are not compatible with SPICE tools. To further evaluate the performance of β-Ga_2O_3 SBDs and their circuit applications, an accurate compact model of the SBDs is necessary. In this study, we propose a compact model, which accurately replicates the experimental characteristics of β-Ga_2O_3 SBDs of various structures. It is a universal model that rules electric characteristics for all β-Ga_2O_3 SBDs.

Device structure and model description. In order to build a unified hybrid compact model for SBDs, we investigate four kinds of β-Ga_2O_3 SBDs. Self-aligned beveled fluorine-plasma-treated diode (SBD1) and Mg implanted edge termination diode (SBD2) are from [7, 8], respectively. Field plated SBDs with monolayer dielectric (SBD3) is from [1], and bilayer dielectric (SBD4) fabricated and tested in our lab is shown in Figure 1(a).

In terms of an actual β-Ga_2O_3 SBD, the series resistance cannot be ignored. As a result, the total forward voltage drop across the β-Ga_2O_3 SBD is the sum of voltage drop across the Schottky contact and series resistance, hence the complete forward *I*-*V* model of β-Ga_2O_3 SBD is

$$I = I_s\left[\exp\left(\frac{q(V-IR_s)}{nkT}\right)-1\right], \quad (1)$$

where I_s is defined as the reverse saturation current, q is the elementary charge, V is the total forward voltage, R_s is the series resistance, n is the ideality factor, k is Boltzmann factor, T is the absolute temperature.

Figure 1(b) shows experimental forward *I*-*V* curves (symbols) of the four β-Ga_2O_3 SBDs at room temperature, it can be seen that all the curves can be divided into two parts: one is the low-voltage non-conduction region, and the other one is the high-voltage conduction region. When the applied voltage is low ($V < V_{\rm on}$, where $V_{\rm on}$ is the threshold voltage of β-Ga_2O_3 SBD), the voltage drop across the Schottky contact is approximately equal to the total forward voltage. Hence, Eq. (1) can be reformulated as

$$I = I_s\left[\exp\left(\frac{qV}{nkT}\right)\right]. \quad (2)$$

On the contrary, when the applied voltage is high ($V > V_{\rm on}$), the voltage drop across the series resistance is predominant. Consequently, β-Ga_2O_3 SBD can be regarded as a resistance, and Eq. (1) is simplified to

$$I = \frac{V-V_{\rm on}}{R_s}. \quad (3)$$

As mentioned above, the complete forward *I*-*V* model can be expressed as a piecewise model with (2) and (3) at low-voltage non-conduction region and high-voltage conduction region, respectively.

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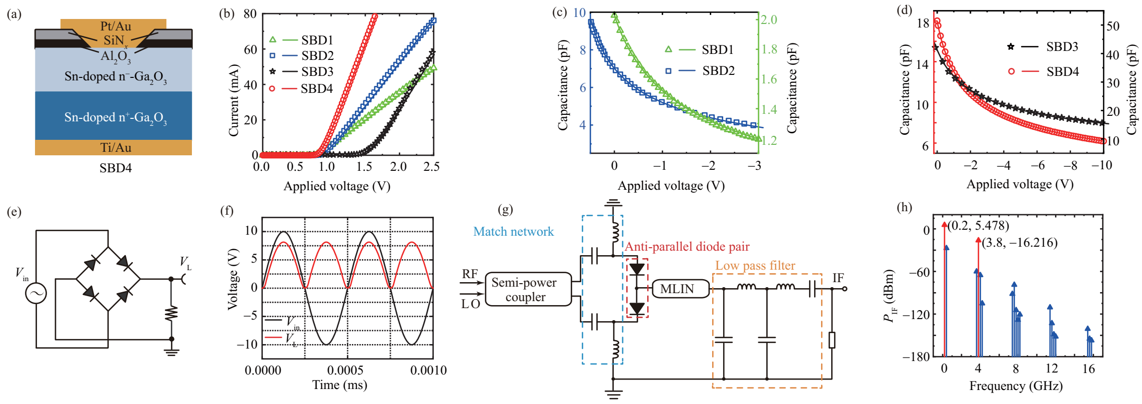

Figure 1 (Color online) (a) Cross-sections of SBD4; (b) experimental forward *I-V* curves (symbols) and *I-V* model (solid lines); (c), (d) experimentally measured *C-V* curves (symbols) of SBD1, SBD2, SBD3, and SBD4 and corresponding *C-V* model (solid lines); (e) configuration of the full-wave rectifier circuit; (f) input and output voltage waveforms of the full-wave rectifier circuit under the frequency of 2 MHz; (g) illustration of the mixer circuit; (h) the output power component vs. frequency of the mixer.

The frequency behavior or switching characteristic of β-Ga_2O_3 SBD can be modeled by a variable capacitance. Measured *C-V* curves of the four β-Ga_2O_3 SBDs at room temperature are shown in Figures 1(c) and (d) (symbols). The width of the depletion region of β-Ga_2O_3 SBDs can be expressed as

$$W = \sqrt{\frac{2\epsilon_s}{qN_D}(V_{bi} + V_R)}, \tag{4}$$

where ϵ_s is dielectric constant of β-Ga_2O_3, N_D is doping concentration, V_{bi} is zero-bias build-in potential, and V_R is the reverse voltage applied to β-Ga_2O_3 SBD. The width of the depletion region varies with the reverse voltage, so that the depletion region is equivalent to a variable capacitance

$$C = A\frac{\epsilon_s}{W} = A\sqrt{\frac{q\epsilon_s N_D}{2(V_{bi} + V_R)}}. \tag{5}$$

Eq. (5) is the *C-V* model of an ideal SBD. In order to implement the *C-V* model into the SPICE simulator, Eq. (5) needs to be reformulated as

$$C = \frac{C_{j0}}{(1 - \frac{V_R}{V_{bi}})^M}, \tag{6}$$

where C_{j0} is the depletion capacitance at $V_R = 0$, and M is the fitting parameter considering the non-ideal effects.

Model verification and circuits application. In order to evaluate the accuracy of the proposed hybrid compact model, the simulation results of the model are compared against experimental data. In Figure 1(b), the simulation results from our forward *I-V* model are well consistent with the experimental *I-V* curves of the four β-Ga_2O_3 SBDs. Besides, an excellent correlation between the *C-V* model and measured *C-V* curves is shown in Figures 1(c) and (d).

Finally, for evaluating the model's SPICE-compatibility, SBD4 is used as an example in full-wave rectifier and mixer circuits simulation. Figure 1(e) shows the configuration of the rectifier circuit. The input alternating current (AC) signal with a 10 V peak-to-peak value is selected for the frequency of 2 MHz. The simulation results are shown in Figure 1(f). Also, a mixer circuit contained a pair of anti-parallel SBDs is shown in Figure 1(g). The output spectrums of the mixer are depicted in Figure 1(h). It can be seen that the output signal at the frequency of 200 MHz has the largest power, and the signal is the desired intermediate frequency precisely.

Conclusion. We develop a unified hybrid compact model of a different structure β-Ga_2O_3 SBDs for full-wave rectifier and mixer applications. The model results are compared with experimental data, and a good match was attained. Its SPICE-compatibility for circuit simulation is demonstrated in the rectifier and mixer. Considering the universality of this model, it can be practical to characterize β-Ga_2O_3 SBDs with other structures and further evaluate their performance in various circuits.

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